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TITLE

EXPERIMENTAL MEASUREMENTS IN A RADIO FREQUENCY DISCHARGE HEATED SUPERSONIC FLOW: EVALUATION OF A POTENTIAL ELECTRIC PROPULSION THRUSTER

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Experimental Measurements in a Radio Frequency Discharge Heated Supersonic Flow: Evaluation of a Potential Electric Propulsion Thruster

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Abstract

An operational radio frequency discharge-driven supersonic flow system, which utilizes an inductively and capacitively coupled plasma (ICCP) tube to produce high enthalpy source gas, is described. The ICCP coupled to a properly designed nozzle represents a potential electric propulsion device. The high gas temperatures achieved in the plasma discharge (> 5000 K) and the electrodeless nature of the tube's operation offers potentially high thruster performance coupled and long operational lifetime. A preliminary characterization of the current system was established using emission and probe-based measurements. A nominal peak specific impulse of 155 s was estimated for operation with argon. The calculated thrust based upon the peak velocity and mass flow through the device is 1.1 N.

Introduction

It is generally recognized that to accomplish the mission goals set forth by the Space Exploration Initiative (SEI) requires continued development of advanced propulsion concepts and technology. Electric propulsion appears to be particularly well suited for SEI missions where long flight times are not of concern[1]. Examples of such missions include transfer from low earth orbit (LEO) to geosynchronous earth orbit (GEO) and cargo transport missions to the moon and other planetary bodies. The high I_{sp} capability of electric propulsion systems offers distinct advantages over chemical systems in both reduction of required on-board propellant and an increase in orbit-raising mass delivery. Beattie and Penn[2] calculate that a vehicle executing a maneuver with a velocity change, Δv, of 6000 m/s shows a five-to-one reduction in propellant mass that must be delivered to LEO as the specific impulse of a spacecraft increases from 300 (chemical propulsion) to 3000 s (electric propulsion). In addition, they calculate that for the same Δv, an electric thruster operating with an I_{sp} of 1000 s could deliver nearly four times the mass to orbit as could a chemical system with an I_{sp} of 300 s.

* Member AIAA

Electric propulsion thrusters are classed into three categories, namely, electrothermal, electrostatic, and electromagnetic. The ICCP or radio-frequency heated thruster, depicted schematically in Fig. 1, is classified as an electrothermal device along with arcjets, resistojets, microwave and laser-sustained thrusters. With such devices the propellant is heated to high temperature by various mechanisms such as DC arcs, resistive elements and plasma discharges, and then expands through a throat and nozzle to produce thrust. The propellant exhaust velocity for such thermal thrusters is proportional to $T^{1/2}$, where T represents the temperature of the propellant before expansion. These electric propulsion thrusters generate very high source temperatures such that their propellant exhaust velocity and hence operational I_{sp} are high. For example, Power and Chapman[3] have projected I_{sp}'s in the 3000 to 4000 s range for a microwave plasma thruster operating with hydrogen propellant. DC arcjets have recently exhibited I_{sp}'s greater than 1000 s in tests with hydrogen propellant[4].

The primary advantage of the ICCP thruster is its electrodeless mode of operation. The absence of gas contacting electrodes has several advantages including potentially long operational lifetimes, reduced plume contamination, and enhanced operating efficiency due to direct deposition of energy into the propellant. In addition, the plasma discharge can be maintained in a free-floating mode; that is it does not contact the walls of the plasma tube. Such operation reduces the reliance on high temperature materials for plasma tube construction.

The RF thruster concept has been considered previously. Pollard, et al.[5] evaluated the performance of a lab-scale thruster operating with several gas mixtures and driven by a 100 watt RF supply (36 Mhz). Molecular-beam sampling was used to characterize the velocity distribution of the flows along the nozzle plume centerline. For He/O_2 mixtures, a centerline discharge velocity of 3.7 km/s was measured corresponding to an I_{sp} of 377 s. The corresponding thrust value for the utilized 3.4 mg/s flow rate is 12.6 mN. Bond, et. al[6] performed a preliminary characterization of an vortex-stabilized RF thruster (2 MHz, 6 kW supply) on the basis of measured exhaust chamber pressure rise and nozzle characteristics. For argon flows, they measured a peak specific impulse of 123 s. Rhodes and Keefer[7] developed a computational model to describe the behavior of a bluff-body stabilized argon-burning RF induction torch for the purpose of designing high power (and flow rate) gas heaters for supersonic combustion applications. Their predictions indicate that the addition of a disk or other appropriate body upstream of the coil region will stabilize the plasma discharge such that tube operation under conditions of high mass flow rate will be possible. Such a conclusion has relevance to ICCP thruster design as it may increase operation efficiency and thrust values.

General Characteristics of the ICCP Thruster

The RF or ICCP thruster relies upon a plasma discharge to drive the propellant gas to high temperatures. The plasma tube is typically a cylindrical device composed of a non-conducting material like quartz, which is surrounded by a multi-turn (load) coil. The load coil is connected to an RF generator of variable frequency and power. Gas is introduced to the interior of the tube to produce either a static or flowing condition. The basic phenomenon governing the operation of the plasma tube is similar to that behind inductive heating of metals. Application of RF power to the coil generates an axial magnetic field component inside the tube which in turn causes the formation of eddy currents in the partially ionized gas (to oppose the action of the magnetic field). Ohmic heating is then responsible for producing the high gas temperatures. (For additional information on the theory of tube operation, see Ref. 9). Initial gas ionization is accomplished through some type of ignitor (which is typically withdrawn after the plasma is established) or by application of the RF field (self ignition through local breakdown due to formation of intense electric fields). The variable frequency capability inherent to RF generators, typically available through adjustment of the tank circuit capacitance and inductance, allows for proper matching of generator power to the plasma load.

The ability to sustain an RF plasma discharge is dependent upon several factors including the physical properties of the gas in the tube (e.g., electrical conductivity), the tube's physical and electrical configuration as well as tube operating pressure and gas mass flow rate. Other important operational considerations include the amount of RF power available to supply to the tube and the operating frequency of the generator. A plot of the minimum amount of plate power necessary to sustain a plasma discharge as a function of frequency for hydrogen, argon, and air at different pressures is shown in Fig. 2 (after Pool, et al., ref. 9).

Los Alamos ICCP Driven Flow System

An RF discharge driven flow system has been constructed at Los Alamos to generate high temperature, supersonic gas flows for various aero-chemical/thermal investigations including supersonic combustion[10]. One of the major advantages of the ICCP tube is that it effectively minimizes flow contamination and thus the potential influence of such contamination on chemical processes occurring in the flow (such as during combustion). A diagram of the primary components of this system is shown in Fig. 3. Although not designed for such an application, the resemblance of this system to an RF thruster test stand is obvious. The major components comprising the ICCP flow system have been described elsewhere[11] but a review of its construction is appropriate for this paper. As seen in Fig. 3, the major components of this system are the plasma tube, transition or coupling apparatus, cooled supersonic nozzle, expansion chamber and heat exchanger. A throttle valve, positioned downstream of the heat exchanger is used to both isolate the expansion chamber from the pumping system as well as adjust the background pressure in the expansion chamber. A gas cooled (liquid nitrogen boil off) trap is connected to the main evacuation line behind the throttle valve to reduce oil vapor contamination. The assembled components are tied to a gas feed system and evacuated by a high-capacity vacuum pumping arrangement.

Gas is introduced to the system from standard "k" type high pressure gas bottles or from tube trailers. Regulation is accomplished through a combination of conventional regulators, dome-loaded regulators, valves, and flow meters. The vacuum system is comprised of two sets of mechanical booster pumps and a rotary-piston backing pump and has a maximum pumping capacity of 5000 CFM (expansion chamber pressure as high as 25 torr). A blowdown capability is also available.

The rectangular expansion chamber contains multiple windows along each of its sides to provide optical access to the nozzle discharge and for the use of non-intrusive laser diagnostics to characterize the flow. The water-cooled heat exchanger, connected at the downstream end of the chamber, cools the high temperature gas stream for evacuation by the pumping system. Working off of house cooling water, the heat exchanger can safely remove up to 150 kW from the gas stream.

The Los Alamos (Hull) ICCP Tube

The unique component of this flow system and the one most directly relevant to a discussion of RF thrusters is the inductively and capacitively coupled plasma tube. A photograph of this tube, recorded during actual operation, is presented in Fig. 4. This plasma tube is of in-house design[12] and quite novel in its construction. It represents an attempt to combine the features of the shielded and unshielded plasma tubes to produce a tube with superior operating characteristics. The plasma discharge is contained and isolated from the quartz mantle by a series of overlapping chevron-shaped segments. The segments are cooled by high pressure water supplied through a manifold located upstream of the discharge region. The quartz mantle (1.5" OD, 0.25 " thick wall) is O-ring sealed at this manifold. This segmented shield, easily discernible in Fig. 4, provides several important functions. As noted previously, it isolates the plasma discharge from the cuter quartz cylinder thereby preventing mantle failure in the event of radial plasma expansion. Unshielded tubes rely primarily upon a sheath gas for such isolation as well as to cool the outer quartz mantle. Other schemes have been devised to simultaneously cool and protect the mantle but none, including the sheath gas method, have proved entirely successful over the desired range of operating conditions. The unique segment design of the Los Alamos ICCP tube eliminates direct line-of-sight between the discharge and the surrounding load coil. Such a design reduces the amount of UV radiation escaping from the discharge region and ionizing the air in the gap between the load coil and mantle. Such ionization can result in electrical breakdown and arcing which in turn can "punch" a hole through the quartz. In addition, the shield can be operated in different electrical modes (i.e., floating, biased, or grounded) which can greatly influence the tube's ability to sustain a plasma discharge. A quartz window in a water-cooled flange located at the far upstream end of the tube, provides visual access to the tube's interior and allows for probing of the plasma discharge with various optical techniques. Gas is introduced to the interior of the plasma tube through a channel in the manifold which supplies water to the shield segments. With the current design, gas is injected through a circular gap in an attempt to generate a laminar gas profile through the load coil region. Certain other unique features of this Hull tube, which could positively enhance tube performance levels, are currently undergoing patent review and can not be discussed here.

The plasma tube is connected to a water-cooled copper flange which in turn is coupled to a transition apparatus. The transition apparatus is essentially a water-cooled channel which is connected to a nozzle located in the interior of the expansion chamber. This rectangular nozzle, pictured in Fig. 5, incorporates straight wall, converging and diverging sections to produce a supersonic exit flow. The fact that the nozzle is not directly coupled to the exit of the plasma tube, as would be done for an actual thruster, and its non-optimum rectangular configuration, reduces the maximum attainable exhaust velocity (and hence I_{sp}). Thus, the current system design (although necessary for the current combustion experiments), is not optimized for a RF thruster application. Nevertheless, measurements of the operating properties of this system can provide an estimate of its potential as an thruster.

Radio frequency power is supplied to the plasma tube from a 50 kW unit. (A 200 kW generator unit is also available for integration into our laboratory). The generator is comprised of a high-voltage DC power supply and an Hartley-type oscillator section. The oscillator section consists of a tank circuit (capacitance-inductance circuit), amplifier, and feedback circuit. The feedback circuit (tied to the grid of the oscillator triode tube) provides flexibility for matching a wide variety of loads. The load coil that surrounds the plasma tube is connected to the generator tank circuit by a water-cooled coaxial line. Control of the RF power is done by varying the DC voltage level applied to the oscillator tube. The operating frequency of the generator (and hence plasma tube) is determined by the tank circuit. For the 50 kW unit, the output frequency can be varied between 0.15 to 1.0 Mhz. The ability to change the output frequency represents an additional means of load matching. For the current experiments, the operating frequency is 680 kHz.

Results

General Operating Characteristics

The plasma tube has been operated with a variety of gases over a range of pressures and flow rates. Pressures up to 1000 torr with argon has been established along with mass flow rates as high as 120 slm. Other gases including N_2, CO_2, H_2, and O_2 have also been introduced in the tube usually in combination with argon gas. In preliminary testing, the Los Alamos tube exhibits the desired characteristics of both the shielded and unshielded plasma tube, namely, the plasma discharge is maintained without shrinkage as the load coil power is increased. The plasma tube's electrical configuration for the present experiments is a floating shield with the rest of the elements at ground potential. The plasma discharge is observed to be stable throughout the tubes's tested range (pressure and flow rate) although flicker is observed at the high flow rates upstream of the load coils. Such flicker is thought to be indicative of turbulence in the tube. No distinct modal shapes have been visually observed upon inspection of the discharge through the tube's observation port and the plasma radial distribution appears to be quite uniform. Typical tube operating efficiencies, defined as the ratio of the power supplied to the plasma discharge divided by the total power supplied to the tube, is in the range 55 to 65%. One outstanding feature of this plasma tube is its ability to initiate a plasma discharge upon application of the RF field. This "self starting" capability obviates the need for any external initiation mechanism (such as a spark or heated graphite rod).

Emission Spectra

Argon emission spectra have been measured in the nozzle exhaust as well as in the plasma tube discharge. Figure 6 depicts the experimental arrangement utilized to record such spectra. The emitted light is focused onto the entrance slit of a 1/3 m monochromator (ISA model H320) with appropriate optics, separated by a 1800 gr/mm grating and amplified using photomultiplier tube (Hammamatsu R666S and/or 1P28A). The signal is sent through an amplifier (Tektronix AM502) and recorded on a strip chart recorder. A similar setup is used for measuring plasma discharge parameters in the plasma tube. Figure 7 shows a partial emission spectrum for an argon discharge recorded in the interior of the plasma tube. In general the emission spectra were recorded over a wavelength range spanning 4000 - 8000 Π. Characteristic argon emission lines are observed in all sets of spectra, however, there is a distinct lack of ionized atom lines. Temperatures can be estimated from such spectra utilizing several methods including the single atomic line method, two line radiance ratio method, and an atomic Boltzmann plot[13]. We have used the atomic Boltzmann plot technique to estimate local plasma temperatures. With an optically thin radiation source, the intensity I_{nm} for an atomic transition from an upper state n to a lower level m is given by[14]:

$$I_{nm} = (1/4\pi) n_a [g_n/Z_a(T)] A_{nm} (hc/\lambda_{nm}) \exp(-E_n/kT), \qquad (1)$$

where,

l = the path length of the source,
n_a = the concentration of atom "a",
g_n = the statistical weight of level n,
$Z_a(T)$ = the partition function of "a",
A_{nm} = the probability of transition,
h = Planck's constant,
c = the speed of light,
g_{nm} = the emitted line wavelength,
E_n = the upper state energy,
k = Boltzmann's constant and,
T = the excitation temperature.

The atomic Boltzmann method is essentially a plot of the logarithmic form of Eq. 1, namely,

$$\ln[I_{nm}\lambda_{nm}/g_n A_{nm}] = C - E_n/kT. \qquad (2)$$

The excitation temperature is derived from the slope of the "best fit" straight line fitted to a plot of the left hand side of Eq. 1 versus upper state energy, E_n. Figure 8 represents one such plot. At a tube pressure of 100 torr, the excitation temperature was determined to be approximately 5300 K. As the tube pressure increased to 500 torr, T_{exc} dropped to 4500 K. Such a drop may be attributed to increased cooling by the high rate of introduction of ambient argon into the discharge region. Excitation temperatures were determined in the nozzle exhaust as well. For a nozzle stagnation pressure of 100 torr, T_{exc} was equal to 4600 K. Because of the low densities in the exhaust, however, the expanding flow is most certainly in a non-equilibrium state. Under such conditions, the excitation temperature is not equal to the gas kinetic temperature.

Probe Based Measurements

Intrusive probe measurements can be utilized to estimate flow velocities in the ICCP supersonic nozzle exhaust. A photograph of the nozzle exhaust pattern as well as the pitot tube used to measure impact pressure distributions is shown in Fig. 9. Velocity measurements are, of course, useful for determining thruster I_{sp}, an important indicator of thruster performance. Total or impact pressures made using a pitot tube provide a means of determining the local Mach number distribution. If the flow is assumed to undergo an isentropic expansion through the nozzle, the Mach number can be estimated knowing the nozzle source or stagnation pressure. When the local Mach number and stagnation or static temperature are known, the mean velocity can then be calculated. (Calculations performed with the Aerotherm Chemical Equilibrium computer code (ACE) show that for a monatomic gas like argon, the ratio of specific heats and the gas constant are not strongly dependent on temperature up to 5000K).

A uncooled pitot tube made from a high temperature alloy (Haynes #230) was coupled to a 250 torr pressure transducer (Validyne model AP-10). The pitot tube has an OD of 3.18 mm and a wall thickness of 0.96 mm. The flow facing end was flattened to produce an opening approximately 1.7 mm wide and 0.25 mm high. The tube was connected to a traverse system that allowed for vertical scans across the nozzle exit face. The high temperature stream represents a harsh environment for intrusive measurements and limits the amount of time the pitot tube can be exposed to the flow without suffering structural damage. The probe response time is adequate, however, to allow fairly rapid scans across the flow. Several impact pressure distributions are shown in Fig. 10 recorded at successive positions, x, downstream of the nozzle exit. The characteristic free jet expansion bow shock structure is evident at the wings of the pressure scans, particularly for increasing x. The nozzle stagnation pressure during these scans was 80 torr. A flow centerline mach number was calculated from this set of scans and is listed in Table I as a function of downstream position.

Table I. Calculated Centerline Mach Numbers, M(x)

x (cm)	Mach Number, M(x)
0.03	1.6
0.72	4.7
1.7	5.3

3.4	6.4

Estimating the Nozzle Stagnation Temperature

The nozzle stagnation temperatures established during the pitot tube scans was estimated via two indirect measurement techniques. One method is based upon a knowledge of the choked mass flow rate, stagnation pressure, nozzle throat size, and various gas parameters. The other technique utilizes ratios of stagnation pressure and temperature, for constant mass flows, with the plasma tube on and off.

The expression for mass flow rate as a function of supply and nozzle conditions is given as:

$$m = [p_o A^* / (RT_o)^{1/2}] Q \ , \qquad (2)$$

where:

$$Q = [\gamma (2/\gamma+1)^{(\gamma+1)/(\gamma-1)}]^{1/2} \ , \qquad (3)$$

in which p_o is the nozzle stagnation pressure, T_o is the nozzle stagnation temperature, A* the nozzle throat area, γ the ratio of specific heats, and R the gas constant. By measuring the mass flow rate, p_o, and A^*, the stagnation temperature can be determined. With this technique, To, is calculated to be 2385 K. The "hot flow" stagnation temperature was estimated by another method. For constant mass flow rates,

$$T_o^H = [(p_o^H / p_o^C)(T_o^C)^{0.5}]^{0.5}, \qquad (4)$$

where, T_o^H is equal to the hot flow stagnation temperature, T_o^C represents the cold flow stagnation temperature, p_o^H is equal to the hot flow stagnation pressure, and p_o^C represents the cold flow stagnation pressure. Using Eq. 4, T_o^H is equal to approximately 2200 K, in reasonable agreement with T_o calculated from Eq. 3.

Mean Flow Speed Estimation

The centerline mean flow speed can be estimated knowing both M(x) and T_o. Using isentropic gas dynamic relations, it can be shown that the dimensionless ratio of the mean flow speed, u(x), to the stagnation sound speed, a_o, can be expressed as,

$$[u(x)/a_o]^2 = 2/\{2/[(M(x))^2 + (\gamma-1)]\} \qquad (5)$$

For a T_o of 2385 K, the stagnation sound speed is 909 m/s. The calculated local mean flow speed along with the corresponding I_{sp} is presented in Table II.

Table II. Mean Flow Speeds and I_{sp}'s

x (cm)	u(x) km/s	I_{sp} (s)
0.03	1.05	107
0.72	1.48	148
1.7	1.50	153
3.4	1.52	155

If all the nozzle stagnation enthalpy was converted to translational kinetic energy, the maximum attainable flow speed can be found using,

$$u_{max} = (2/(\gamma-1))^{0.5} a_o \qquad (6)$$

Using Eq. 5, u_{max} = 1.57 km/s, indicating that for our argon flow, a considerable amount of initial enthalpy has been converted to translational energy.

If the nozzle was coupled directly to the plasma tube and the measured tube excitation temperature was to equal the gas stagnation temperature, u_{max} increases to approximately 2.3 km/s (I_{sp} = 235 s). If we use a lighter mass propellant, such as hydrogen, and the fact that the exhaust velocity is proportional to the inverse square of the propellant mass, then for the same source temperature, we can project Isp's for the RF thruster in excess of 1000 s, a very respectable value.

Future (Potential) Activities

The Los Alamos plasma tube represents a novel device incorporating features of both a shielded and unshielded tube. Its use as a high temperature gas source for RF thruster application is promising. Extensive testing of the plasma tube beyond its current use is necessary, however, to fully characterize the performance of the device. System variables such as gas species, gas pressure, flow rates, tube operating frequency, and electrical configuration need to be examined to maximize efficiency and define plasma tube performance. Testing with a properly designed nozzle attached directly to the plasma tube exit to maximize attainable flow velocities will allow for a more thorough determination of thruster capabilities. In addition, more refined measurements of nozzle exhaust parameters, such as velocity, need to be made to accurately establish thruster performance. Non-intrusive diagnostics such as planar laser induced fluorescence, currently being utilized in our laboratory for reactive flow characterization, may be useful in this application. Finally, although the plasma tube has been operated with H_2, more definitive testing is necessary to evaluate tube performance with this attractive propellant gas.

Summary

A potential ICCP thruster has been described. The ICCP tube offers a means of establishing high temperature gas flows without lifetime-limiting, gas contacting electrodes. The described flow apparatus is not optimized for an RF thruster application as the nozzle is separated from the plasma tube and rectangular in design. Such assembly, although well suited for current combustion studies, results in a reduction of gas temperature at the thrust generating nozzle entrance and a concomitant loss in flow velocity. Properly configured and operationally optimized, the ICCP has potential as an alternative, low thrust, electric propulsion device.

Both non-intrusive (emission measurements) and probe-based measurement techniques have been used to estimate conditions in the plasma tube and nozzle discharge. On the basis of these measurements, discharge velocity values have been calculated. For argon flows, a maximum I_{sp} of 155 s has been measured This number could scale considerably higher with the use of a lighter propellant such as hydrogen.

Acknowledgement

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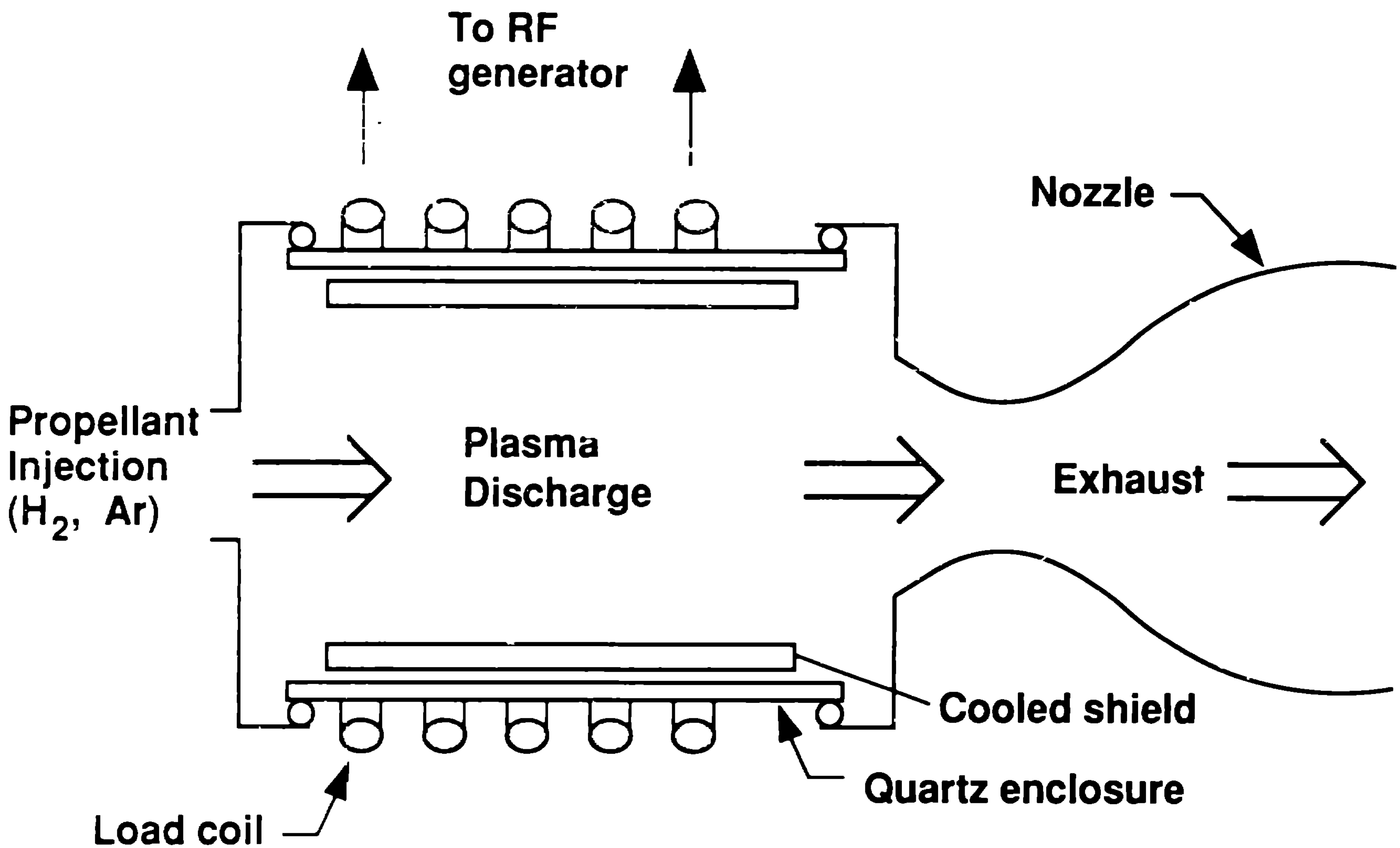
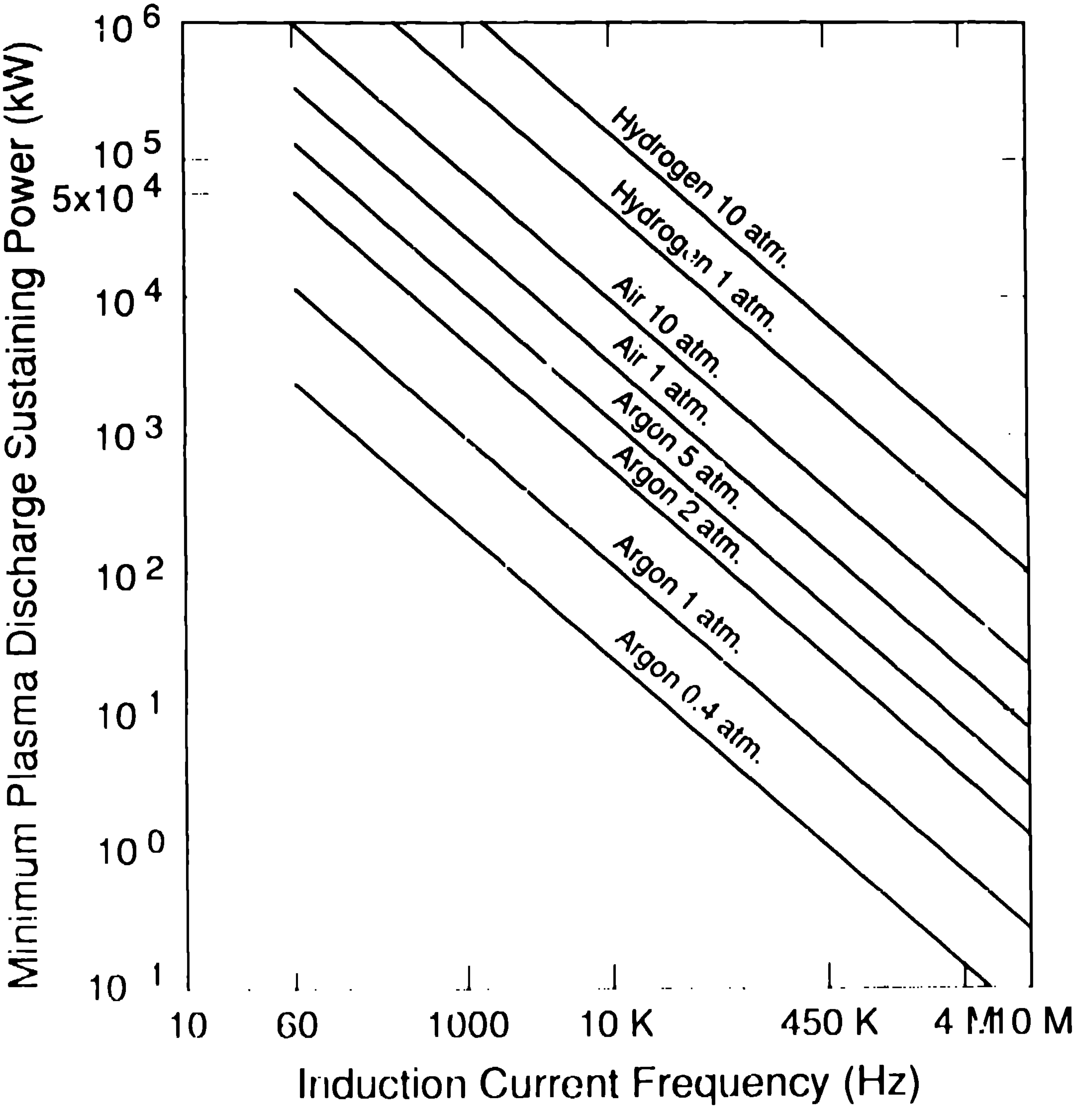
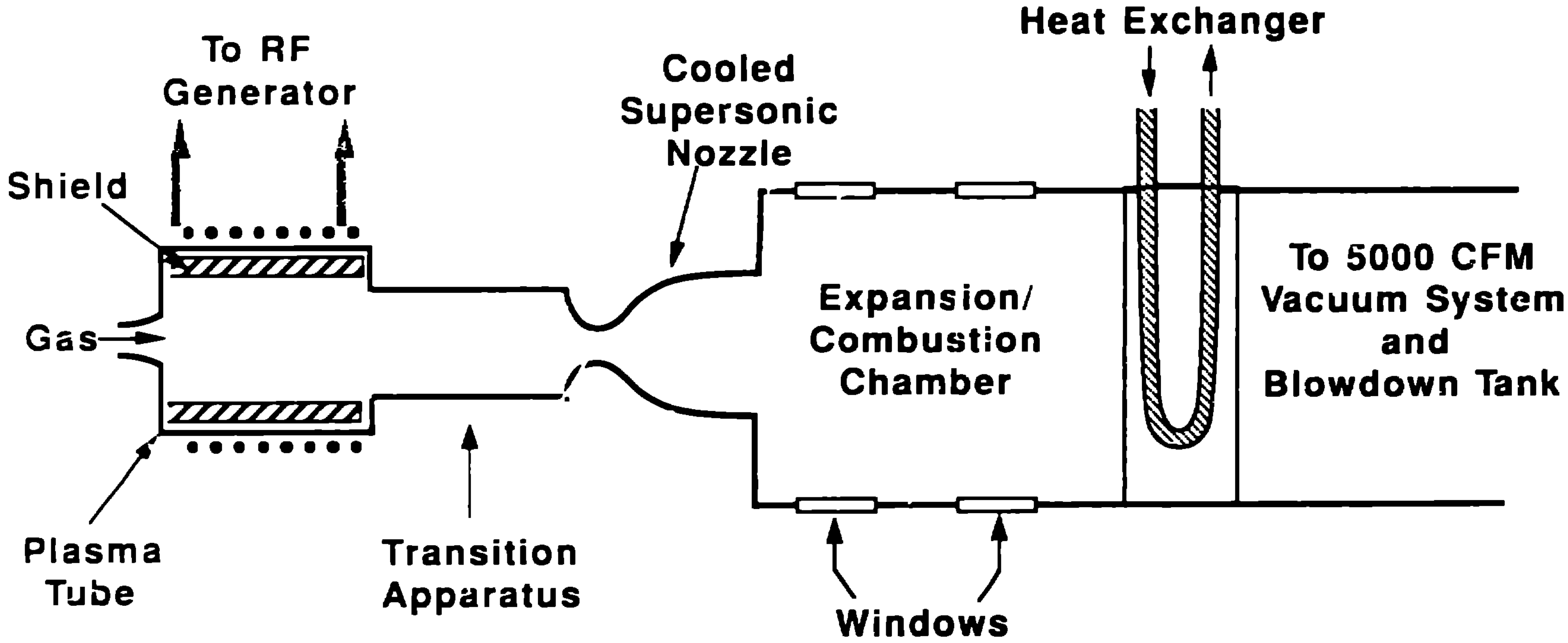

To RF generator
Nozzle
Propellant Injection (H_2, Ar)
Plasma Discharge
Exhaust
Cooled shield
Quartz enclosure
Load coil



Minimum Plasma Discharge Sustaining Power (kW)
10 6
10 5
5x10 4
10 4
10 3
10 2
10 1
10 0
10 1
Hydrogen 10 atm.
Hydrogen 1 atm.
Air 10 atm.
Air 1 atm.
Argon 5 atm.
Argon 2 atm.
Argon 1 atm.
Argon 0.4 atm.
10
60
1000
10 K
450 K
4 M
10 M
Induction Current Frequency (Hz)



To RF Generator
Shield
Gas
Plasma Tube
Transition Apparatus
Cooled Supersonic Nozzle
Expansion/ Combustion Chamber
Windows
Heat Exchanger
To 5000 CFM Vacuum System and Blowdown Tank

Fig. 3

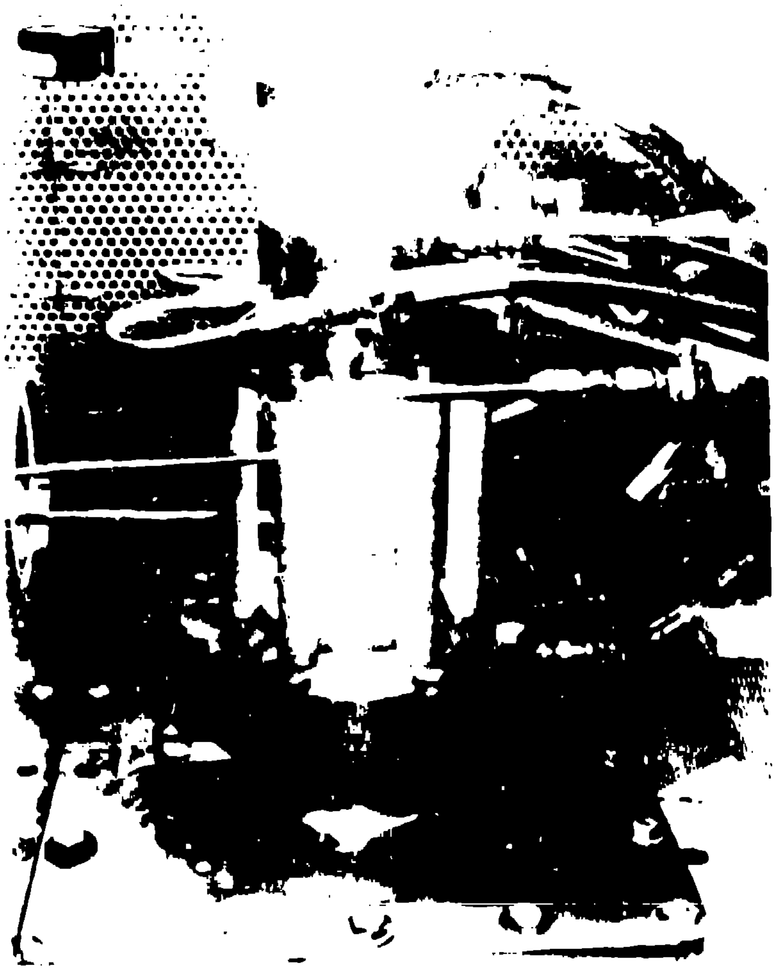


Fig. 5

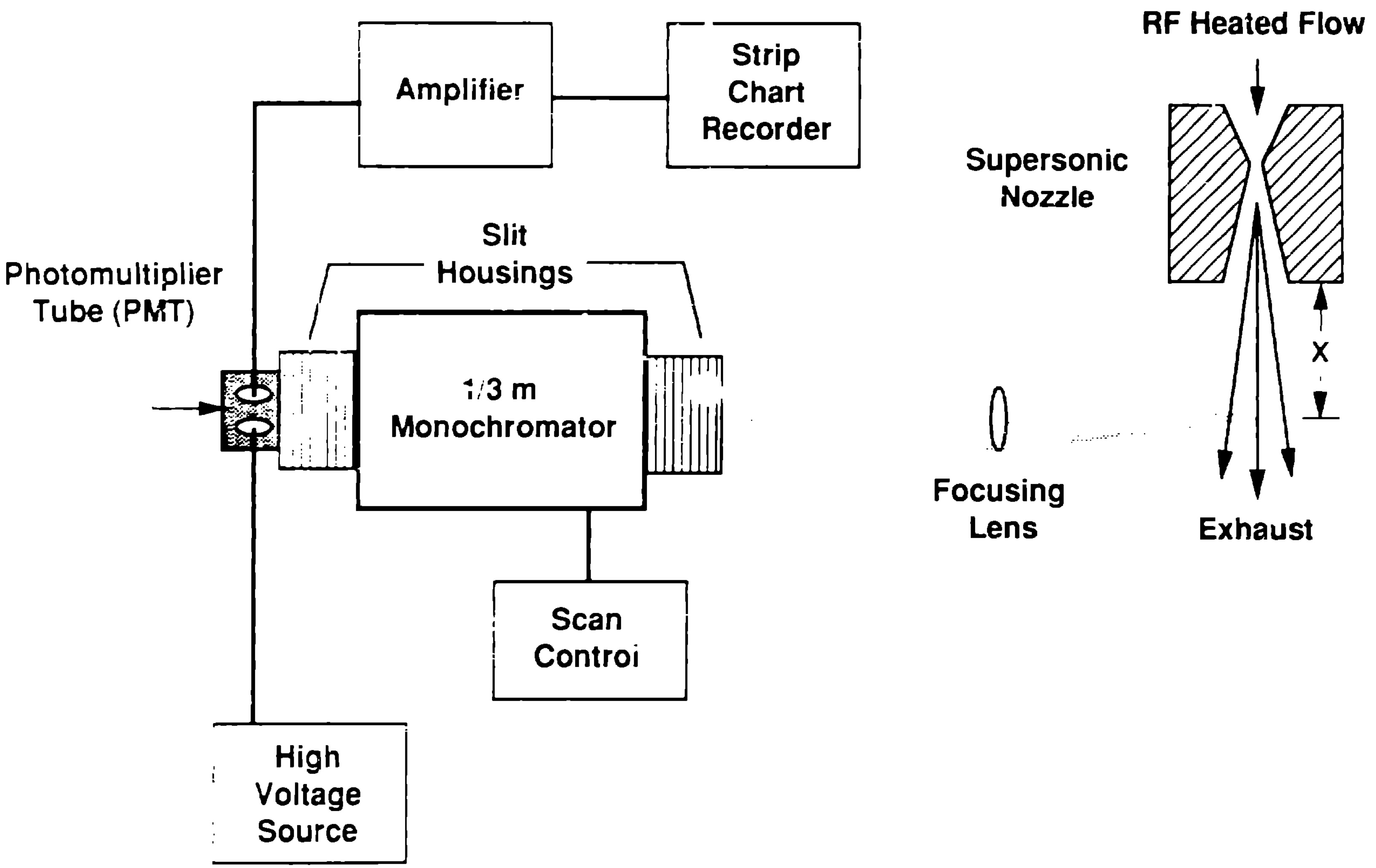
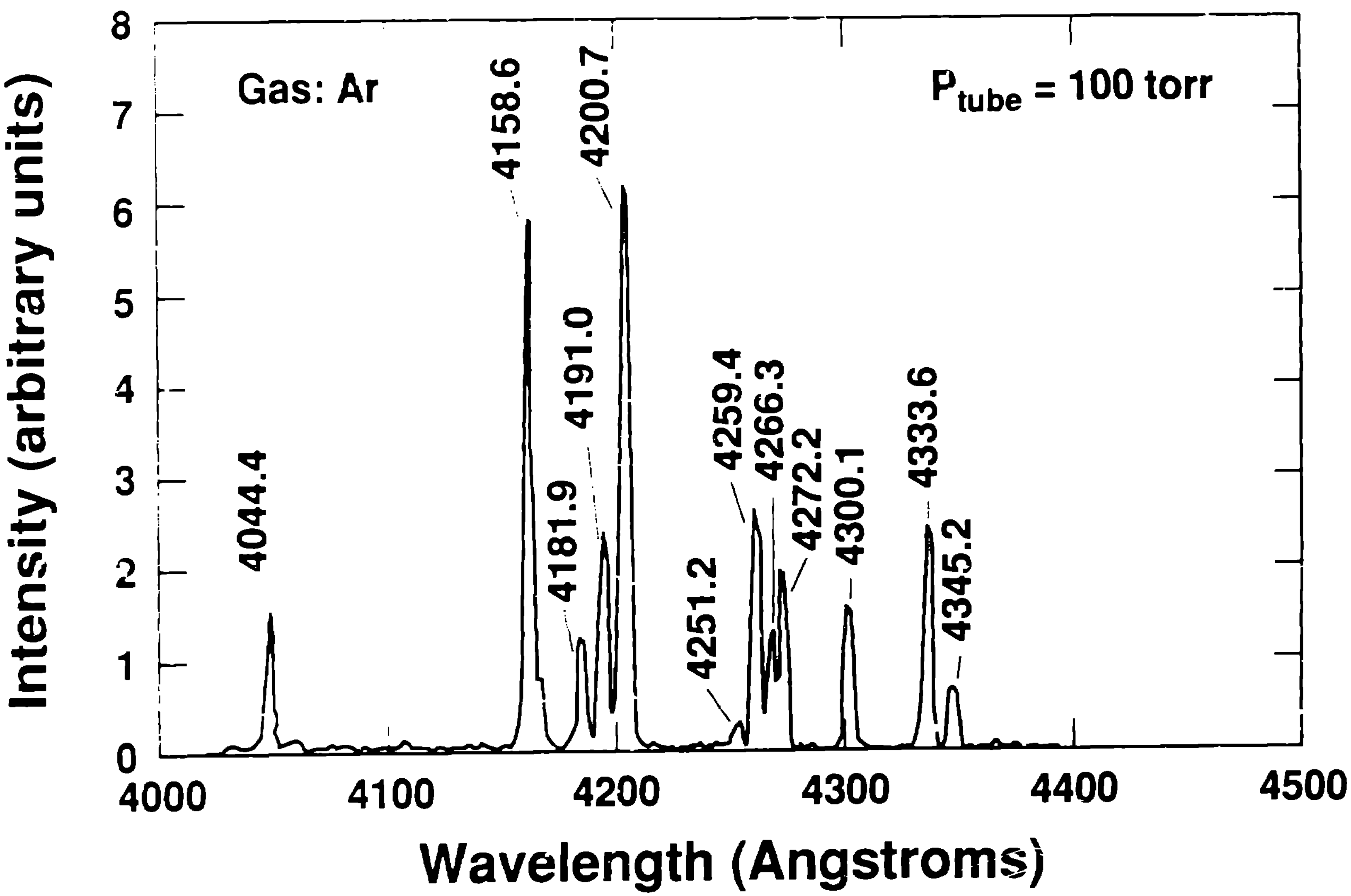

Amplifier
Strip Chart Recorder
Photomultiplier Tube (PMT)
Slit Housings
1/3 m Monochromator
Scan Controi
High Voltage Source
RF Heated Flow
Supersonic Nozzle
X
Focusing Lens
Exhaust

Fig. 5



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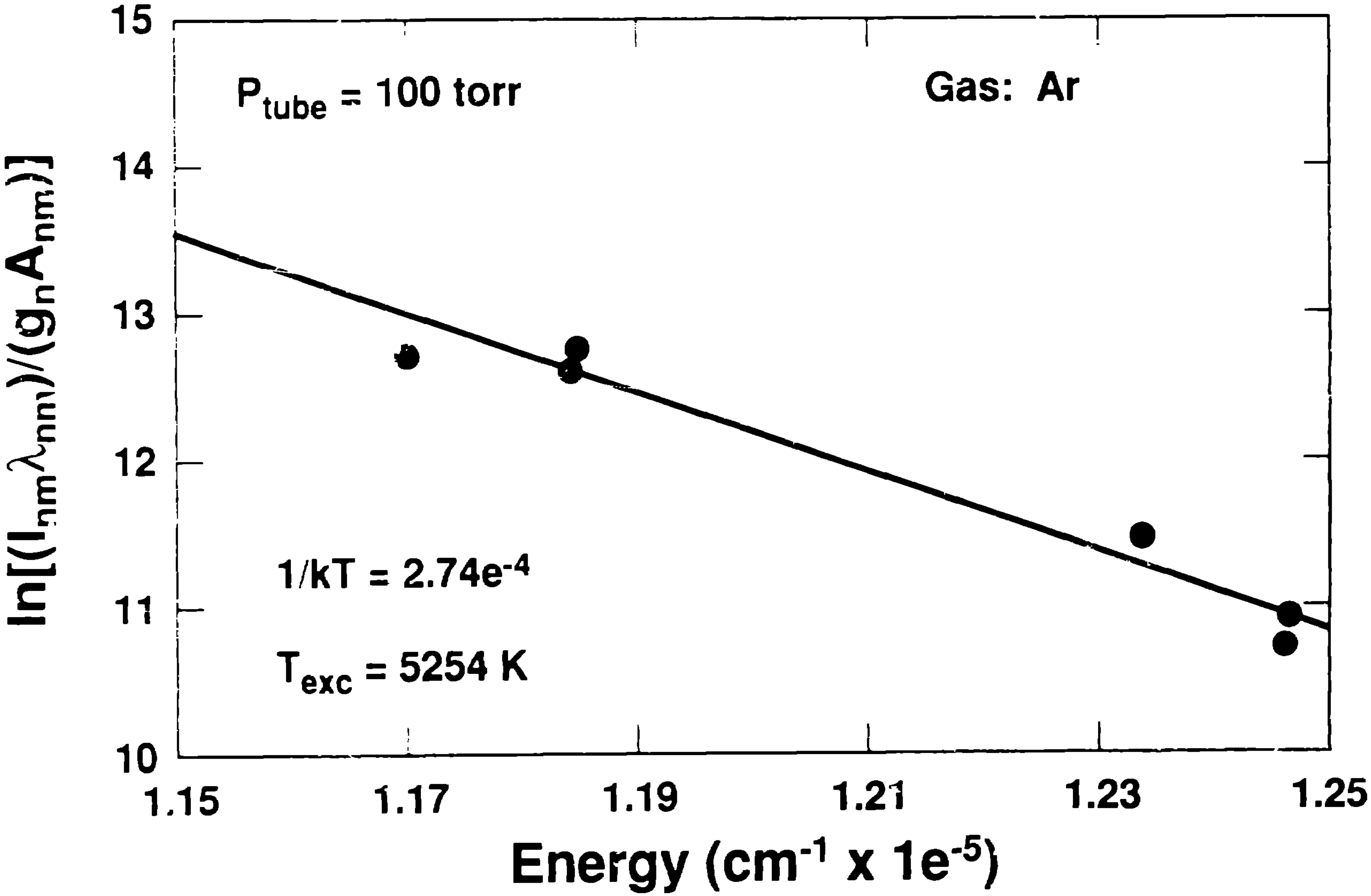

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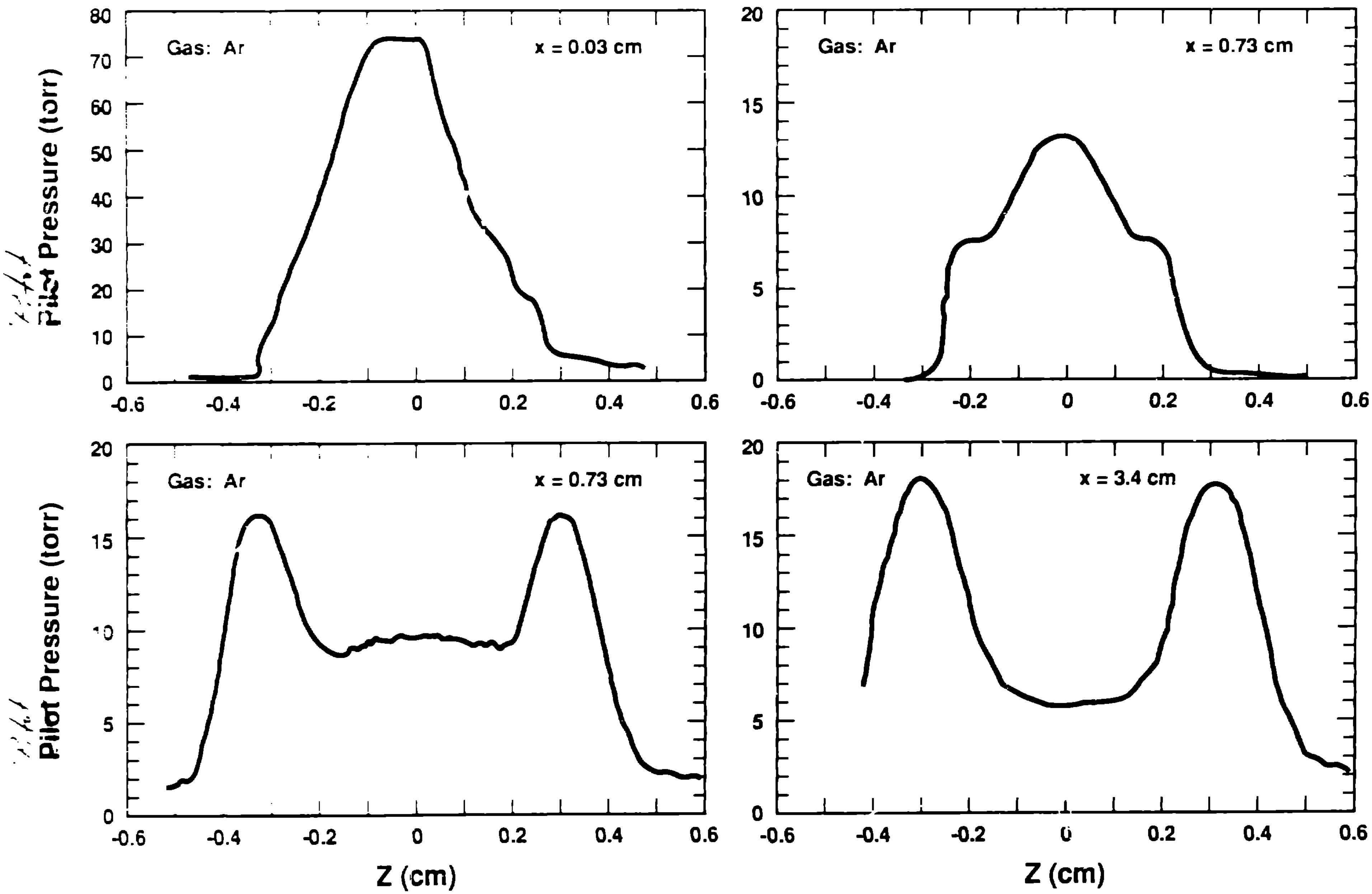
Pilot Pressure vs Vertical Scan Distance



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